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Research Article

Assessment of Network Layouts for CDMA Radio Access

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The aim of this paper is to perform an overall comparison of different network layouts for CDMA-based cellular radio access. Cellular network layout, including base station site locations and theoretical azimuth directions of antennas, can be defined by tessellations in order to achieve a continuous coverage of the radio network. Different tessellation types—triangle, square, and hexagon—result in different carrier-to-interference scenarios, and thus will provide nonequal system-level performance. This performance of a cellular network is strongly related to configuration parameters as base station antenna height, beamwidth, and sectoring. In this paper, a theoretical model is defined for the assessment, which includes numerical analysis and system-level simulations. A numerical analysis was performed first, and then system-level Monte-Carlo simulations were conducted to verify and to extend numerical results. The obtained results of the numerical analysis indicate that a hexagonal "clover-leaf" layout is superior, but the results of system-level simulation give similar performance for the triangular and square layouts. These results indicate also the importance of the antenna height optimization for all layouts. Moreover, the simulation results also pointed out that 6-sector configuration is superior both in coverage and in capacity compared to nominal 3-sector configuration that is typically preferred in coverage-related network deployments in practice.

1. INTRODUCTION TO NETWORK LAYOUTS

New requirements for data communications in mobile networks have accelerated the evolution of the mobile communication systems. This evolution includes the change of radio access first from FDMA (frequency division multiple access) to TDMA (time division multiple access), and finally from TDMA to CDMA (code division multiple access) for 3rd generation mobile technologies as UMTS or CDMA2000. Moreover, recently 4th generation technologies as, for example, LTE (long-term evolution, next generation from UMTS) and WiMAX (broadband access network) have adopted OFDMA radio access to their specifications.

All these radio access schemes utilize frequencies or a certain frequency band slightly in a different manner, and a debate about which access scheme is the most efficient happens continuously. However, most recent and also future planned mobile communication systems are based on CDMA and OFDMA, and it looks that it is commonly accepted that these access schemes are the most efficient ones.

However, the performance discussion of each access scheme should always be linked to network topologies and layouts because these have a strong impact on the final results. First network layout or one of the first ideas about cellular concept was presented in 1947 by Ring [1]. Mobile communication system was patented in the early 1970's [2], and network layouts based on different tessellations, or mosaic as those can also be called, were also presented at the same time [3]. Tessellations create a continuous surface over a plane by using a form of triangle, square, or hexagon, and thus those can be used as a basis for site locations for a network with continuous coverage. MacDonald presented a cellular concept again in 1979 with network layouts based on different tessellations [4]. Moreover, each single hexagon, square, or triangle contained an omnidirectional site or a group of sectors, and thus sectorization was also mentioned in [4].

The cellular concept was further developed by Sundberg, who presented different configurations for omnidirectional, 3-sector, 6-sector layouts, and combinations of these. In [5], Sundberg presented mainly hexagon-based configurations for FDMA/TDMA, and theoretical carrier-to-interference calculations to show the performance of the frequency reuse as a function of cochannel interference (C/I). In the results of [5], it was concluded that 3-sector hexagon layout where 3-sector site was implemented in the corners of the hexagon (equivalent of hexagonal layout in this paper) was superior to omnidirectional configuration. Moreover, Sundberg also concluded in [5] that layouts with combination of three- and six-sector sites and only six-sector sites outperform the 3-sector hexagonal layout. The author also wrote that equivalents of clover-leaf and triangle tessellations presented in this paper are not competitive due to larger relative distance from the site to the corner of the cell.

In early 1980's, Cox [6] compared hexagon and square tessellations for FDMA/TDMA technologies, and noted that in some cases hexagon is better and in some cases square is better. Suzuki et al. [7] continued the work further and presented 6-sector configurations together with uplink C/I calculations. Later in 1980's, Lee [8] presented frequency reuse models for omnidirectional and directional base station antennas. Finally in late 1980's and early 1990's, for example, Palestini in [9, 10] presented simulation results about frequency reuse and frequency planning.

Finally, in late 1990's and early 2000's different studies about optimum beamwidth with different sectoring schemes were presented [11–16], and it was concluded that 3-sector site needs antennas with 65° horizontal beamwidth when base station site is implemented in the middle of the hexagon, and antennas with 90° horizontal beamwidth when base station site is implemented in the corner of the hexagon. Similarly, it was pointed out that $30–40^\circ$ horizontal beamwidth is needed for 6-sector sites in order to achieve optimum performance.

In all results in [3–12, 17], only FDMA/TDMA technologies were considered because cochannel interference was never in a neighbour sector, and typically frequency reuse was always studied. Moreover, comparison of different tessellation results has not been performed with optimum beamwidths. And finally, all results in [3–15, 17] are assuming a constant base station antenna height and constant path loss. Thus, impact of breakpoint distance and propagation slope was not considered especially for strongly interference-related CDMA radio access.

In this paper, the first target is to show the impact of base station antenna height and path loss exponent on the final performance of each tessellation. After showing the optimum configuration for each tessellation, numerical performance comparison is done for CDMA network based on 3-sector sites by utilizing hexagon, square, and triangle layouts. Finally, numerical results are verified and extended by system-level simulations.

2. THEORY

2.1. Tessellations and network layouts

Nominal network layouts are used in mobile radio network design for initial dimensioning and for guidance on selection of the site locations, antenna sectorization, and azimuth directions. Selection of the site locations can follow different rules, but typically a geometric form that enables a creation of continuous network coverage is selected. This criterion is fulfilled by a selection of a regular polygon which forms a tessellation. Only three regular polygons that tessellate as single form exist; triangle, square, and hexagon. Different combinations of site locations and antenna configurations can be formed based on these tessellations. Network layouts based on triangle, square, and hexagon are presented in Figure 1.

The site locations and the antenna azimuths of layouts in Figures 1(a)–1(c) have been selected based on the same principle; the sites are located at the centre of the polygon, and the antennas are pointed to the corners of the polygon. In the layout in Figure 1(d), the site is also located at the centre of the hexagon, but the antennas are pointed to the vertices of the hexagon instead of the corners.

The shaded areas in Figure 1 represent the expected dominance areas of the sites [5]. They indicate that the dominance area of a site follows the polygon shapes in triangle, square, and hexagon layouts in Figures 1(a)–1(c). These layouts are named in this paper, respectively, according to the shape of the site dominance area. The site dominance area of the second hexagon-based layout in Figure 1(d) can be recognized as a leaf of a clover, and the layout has been named as clover-leaf layout [9, 12].

2.2. Propagation model

The target of this paper is to assess the network layouts in macrocellular environment. Thus the empirical COST-Hata model was selected for the analysis. This model was defined in COST231 work [18] for urban macrocell environments and it is developed based on widely used Hata model [19]. The COST-Hata model gives a local average of the signal path loss at a certain distance. The path loss is formulated in the selected model as

$$L = \frac{Cd^{\gamma}10^{\Omega/10}}{G(\theta,\varphi)}, \tag{1}$$

where the first term C is a static term including the effect of carrier frequency (f), base station antenna height (h_{BTS}), an optional area correction factor (M), and a building penetration loss for indoor users (BPL). The effect of a mobile station antenna height is neglected. The term C is formulated in the model as

$$C = 10^{(46.3+33.9\log_{10}f-13.82\log_{10}h_{\mathrm{BTS}}+M+\mathrm{BPL})/10}. \tag{2}$$

The distance dependence of the path loss, that is, propagation slope, is defined in (1) by the path loss exponent γ which is further defined as

$$\gamma = \frac{44.9-6.55\log_{10}(h_{\mathrm{BTS}})}{10}. \tag{3}$$

This definition is part of the COST-Hata model and it presents the path loss exponent as a function of the base station antenna height. In macrocellular environments, the

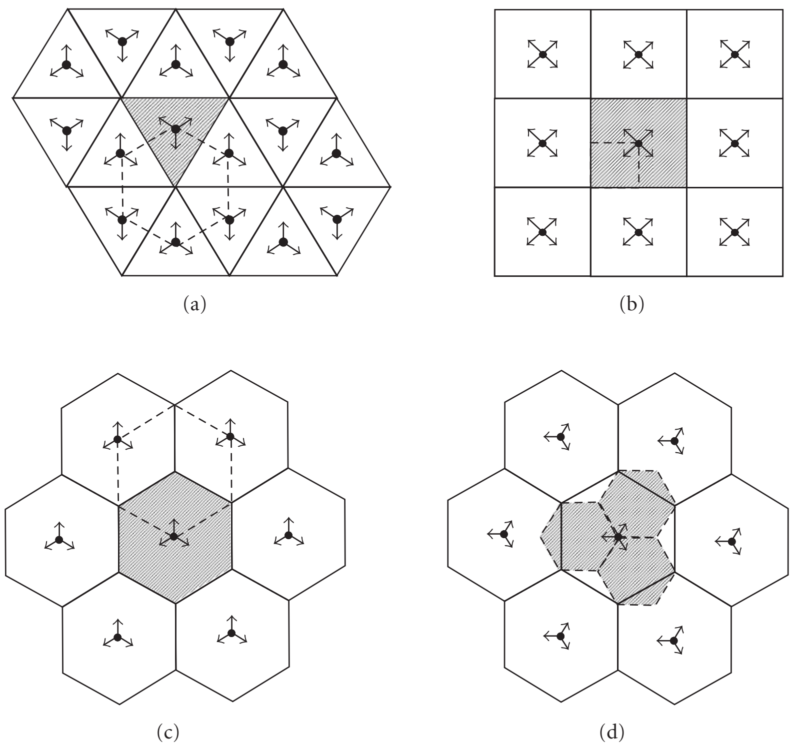

Figure 1: Triangle, square, and hexagon-based cellular network layouts. (a) Triangle, (b) square, (c) hexagonal, and (d) clover-leaf layouts.

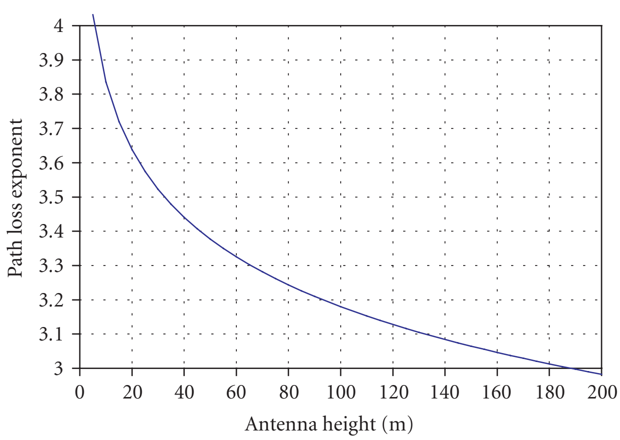

Figure 2: Path loss exponent as a function of antenna height.

signal attenuates faster with lower base station antenna heights. The path loss exponent γ is plotted in Figure 2 as a function of antenna height h_{BTS}. Equation (3) is valid for antenna height in range of 30–200 m, and the path loss exponent decreases from 3.5 to 3 within this range.

The propagation model in (1) includes also a slow fading component Ω. This variable introduces the effect of signal shadowing due to buildings, trees, and other obstacles on the radio path. Ω is a Gaussian distributed variable which has an environment-dependent standard deviation. The standard deviation is typically in a range of 6-7 dB for outdoor, and 9-10 dB for indoor locations in macrocellular environments.

2.3. Antenna selection

Antenna radiation pattern has a dominant effect on the radio network performance. $G(\theta, \varphi)$ represents the antenna gain (azimuth angle θ, and elevation angle φ) in the propagation model (1). Figure 3 [20] presents an example of a practical base station antenna pattern. The antenna patterns are typically characterized by antenna gain relative to isotropic antenna [dBi] or dipole antenna [dBd], horizontal antenna pattern beamwidth, and downtilt in the vertical antenna pattern.

Antenna properties have to be matched to the network layout in order to achieve the optimum performance. The cellular network layout design started with omnidirectional horizontal antenna patterns, but quite soon the results of the sectorized antenna solutions were published [4, 5]. These initial analyses considered theoretical antennas with horizontal beamwidth equal to the sector width. More recent analysis has been done for optimization of the antenna beamwidth for different layouts. S.-W. Wang and I. Wang [11] published results of a 3-sector hexagonal layout (Figure 1(c)) with antenna beamwidth of 100–120 degrees. The authors concluded that the frequency efficiency improves with smaller antenna beamwidth. Wang et al. [12] studied clover-leaf and hexagonal 3-sector layouts with 60-degree and 120-degree antenna beamwidths, respectively. The authors concluded that the 60-degree antenna pattern matches well the sector shape of clover-leaf layout, but 120-degree antenna has high side lobe levels over adjacent sectors in hexagonal layout. Wacker et al. concluded in

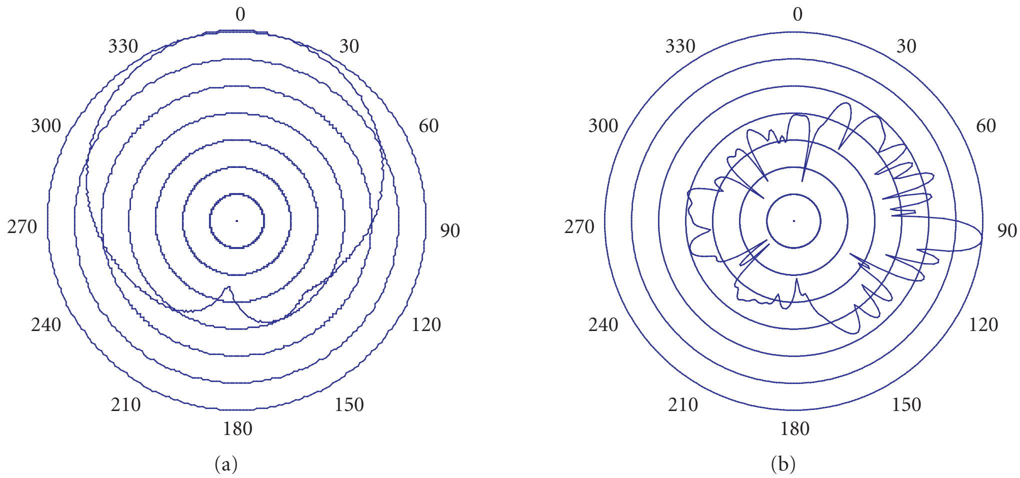

Figure 3: Antenna horizontal (a) and vertical (b) radiation patterns. Antenna gain 17.6 dBi, beamwidth 65 degrees, and electrical downtilt 5 degrees.

[13] that the optimum antenna beamwidth for clover-leaf layout is 65 degrees; other tested beamwidths were 33 or 90 degrees. Johansson and Stefansson [14] studied the optimum opening angle for clover-leaf and hexagonal 3-sector layouts and concluded that optimum values are 60 degrees and 80 degrees for these layouts, respectively.

Also the vertical antenna beamwidth has to be considered in addition to the horizontal beamwidth discussed previously. Vertical beamwidth is defined by the antenna size or height, and cannot be selected as freely as the horizontal one due to practical antenna-size limitations. Commonly used 1.5–2 m antennas provide an antenna beamwidth of 6-7 degrees at 2 GHz band.

The network performance can be further optimized by vertical antenna downtilting. One example of a downtilted antenna pattern can be seen in Figure 3(b), which represents an antenna pattern with 5-degree downtilt. The optimum amount of downtilt depends on the vertical beamwidth, network layout, and antenna height. Niemelä et al. [15] concluded that optimum performance in macrocell environment can be achieved with downtilt close to the vertical beamwidth of the antenna. Itkonen et al. [16] presented results of optimum downtilt and antenna height for maximum capacity, and coverage of clover-leaf and triangular network layouts. These results indicate that the increase of downtilt above 5 degrees provides only a marginal performance gain but requires clearly higher antenna placement.

The characteristics of the antennas that have been selected for the assessment of the network layout are based on the previous results and also on the availability of commercial antenna solutions [20]. The antenna properties are listed in Table 1.

3. LAYOUT PERFORMANCE EVALUATION

Radio network performance can be measured with multiple performance indicators. These can be used to measure the coverage, interference, and system performance. The performance indicators can be solved with closed-form equations, numerical calculations, or simulations.

3.1. Performance indicators

Signal strength or path loss statistics are used as coverage performance indicator in the network layout assessment. Even distribution of signal power across the network coverage area provides basis for good overall performance.

Dominance area size and shape, and pilot signal level measure sector coverage properties and quality. Dominance area of a sector is defined as an area where a sector provides the highest signal level or the lowest path loss compared to other sectors in the network. In single-frequency networks like CDMA networks, the sector dominance area size has a direct effect on the amount of traffic gathered by a sector. The dominance area border can also be considered as the most critical region of the network from the layout performance point of view. Dominance area border between two sectors can be defined as a line with equal path loss to both sectors:

$$L_A = L_B, \qquad \frac{Cd_A^{\gamma}}{G(\theta_A, \varphi_A)} = \frac{Cd_B^{\gamma}}{G(\theta_B, \varphi_B)}. \tag{4}$$

The criteria for dominance area border can be further formulated with equal antenna height as

$$\frac{d_A}{d_B} = \left(\frac{G(\theta_A, \varphi_A)}{G(\theta_B, \varphi_B)}\right)^{-\gamma}, \tag{5}$$

which shows that the relative distance to the dominance area border between the neighbour sites depends on relative antenna gains and propagation slope. The antenna gains are equal on the dominance area border in a symmetrical network layout. In this case, the distance of the dominance border is equal from the neighbouring sites and it is not dependent on the propagation slope.

A measure for network interference level is also required for network layout performance analysis. In a CDMA

Table 1: Selected antenna parameters for different layouts.

	Triangle	Square	Clover-leaf	Hexagonal
Horizontal beamwidth	65	45	65	88
Vertical beamwidth	6.5	6.5	6.5	6.5
Gain, dBi	17.6	19.6	17.6	16.7
Downtilt	5	5	5	5

network, the interference is a sum of three interference sources: own (serving) sector signals, other site/sector signals, and thermal noise. Interference level has to be analysed in uplink (UL) and downlink (DL) directions separately. In downlink direction, the interference at a given location of a network can be presented as

$$\begin{aligned} I_{\mathrm{DL}} &= I_{\mathrm{own}}(1-\alpha) + I_{\mathrm{other}} + P_N \\ &= \frac{P_{\mathrm{own}}}{L_{\mathrm{own}}}(1-\alpha) + \sum_{n\in\mathrm{other}}\left(\frac{P_n}{L_n}\right) + P_N \\ &= \frac{P_{\mathrm{own}}}{L_{\mathrm{own}}}\left(1-\alpha+\sum_{n\in\mathrm{other}}\left(\frac{L_{\mathrm{own}}}{L_n}\right)\right) + P_N \\ &= \frac{P_{\mathrm{own}}}{L_{\mathrm{own}}}(1-\alpha+f) + P_N, \end{aligned} \tag{6}$$

where I_{own} is the total received power from own sector, α is orthogonality, I_{other} is the total received power from other sectors of the network, P_N is a thermal noise, P_{own} is a total transmit power from own sector, L_{own} is a path loss to own sector, P_n is a total transmit power of neighbour sector n, and L_n is a path loss to sector n. Orthogonality α is a measure for level of interference caused by own sector signals. The DL channelization codes are orthogonal ($\alpha = 1$) in Wideband CDMA (WCDMA) technology, but the orthogonality is partly lost ($\alpha < 1$) in wireless radio environment due to multipath propagation. The final form of the equation assumes equal total DL power for all sectors in the network. The ratio of $I_{\mathrm{other}}/I_{\mathrm{own}}$ named as f is a commonly used measure for level of sector overlap and interference in the network layout and it is defined as

$$f_{\mathrm{DL}} = \sum_{n\in\mathrm{other}}\left(\frac{L_{\mathrm{own}}}{L_n}\right). \tag{7}$$

The signal-to-interference-noise-ratio (SINR) represents the quality of the received signal. It is defined at a receiver input as

$$\mathrm{SINR}_{\mathrm{DL}} = \frac{p^{tx}/L_{\mathrm{own}}}{I_{\mathrm{tot}}} = \frac{p^{tx}/P_{\mathrm{own}}}{(1-\alpha+f)+P_N}, \tag{8}$$

where p^{tx} is the power of the transmitted signal. The definition of the $\mathrm{SINR}_{\mathrm{DL}}$ can further be simplified to $\mathrm{SIR}_{\mathrm{DL}}$ by neglecting the thermal noise and the orthogonality, and assuming only one user per sector ($p^{tx} = P_{\mathrm{own}}$) [12],

$$\begin{aligned} \mathrm{SIR}_{\mathrm{DL}} &= \frac{1}{f_{\mathrm{DL}}} = \left(\sum_{n\in\mathrm{other}}\frac{L_{\mathrm{own}}}{L_n}\right)^{-1} \\ &= \left[\sum_{n\in\mathrm{other}}\left(\frac{d_{\mathrm{own}}}{d_n}\right)^{\gamma}\frac{G(\theta_n,\varphi_n)}{G(\theta_{\mathrm{own}},\varphi_{\mathrm{own}})}10^{(\Omega_{\mathrm{own}}-\Omega_n)/10}\right]^{-1}. \end{aligned} \tag{9}$$

In uplink direction, the total interference at the base station receiver can be presented as

$$\begin{aligned} I_{\mathrm{UL}} &= I_{\mathrm{own}} + I_{\mathrm{other}} + P_N \\ &= \sum_{k\in\mathrm{own}} p_k^{rx} + \sum_{k\in\mathrm{other}}\frac{L_{\mathrm{other},k}}{L_{\mathrm{own},k}}p_k^{rx} + P_N, \\ &= (1+f_{\mathrm{UL}})N_{\mathrm{own}}p_k^{rx} + P_N, \end{aligned} \tag{10}$$

where p_k^{rx} is the received power of the user k, $L_{\mathrm{other,k}}$ is the path loss to serving sector of user k who is not served by the (own) sector under consideration. $L_{\mathrm{own},k}$ is the path loss of this user to this sector. All users are assumed to have the same service and equal received power, which is power controlled to the same level p_k^{rx}. N_{own} is the number of users served by the own sector. The ratio of the UL interference caused by the users on neighbouring cells to the UL interference caused by the own sector users is defined as

$$f_{\mathrm{UL}} = \frac{1}{N_{\mathrm{own}}}\sum_{k\in\mathrm{other}}\frac{L_{\mathrm{serv},k}}{L_{\mathrm{own},k}}. \tag{11}$$

Moreover, the performance assessment requires more complete performance measures in addition to coverage and interference performance evaluation. Service probability (availability) can be used to measure a system-specific performance for different network layouts. Service probability measures the availability of the service with a given network configuration, service, and traffic. Unavailability of the service can be caused by lack of either coverage or capacity. Coverage limitation will occur when the required signal quality (SINR) cannot be achieved at the receiver with maximum transmit power of a link. Capacity limitation will occur when the maximum downlink capacity (transmit power) or the maximum uplink capacity (noise rise) of the sector is exceeded.

Service probability is tied to the cell range or even more to sector area, which is the most important performance criterion from the network investment point of view. Thus,

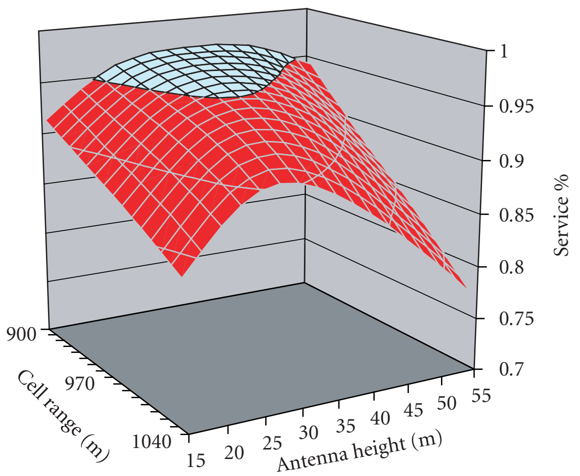

Figure 4: The service probability as a function of antenna height and cell range, and the 95% service probability level.

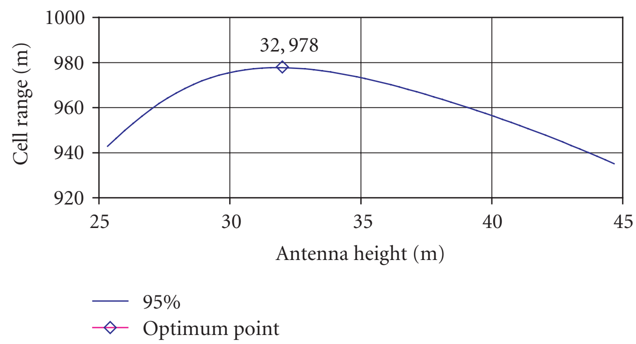

Figure 5: Cell range as function of antenna height at 95% service probability limit.

in order to assess the final performance of different network layouts, the maximum sector area (cell range) should be found for each of these layouts. On the other hand, higher sector area decreases service probability due to lower signal level and higher traffic load per sector. Moreover, maximum sector area is tied to selected antenna height, which has to be optimized for each network configuration. Thus, the service probability should be presented as a function of cell range R and antenna height h_{ant}:

$$P_{\text{Service}} = f(R, h_{\text{ant}}). \tag{12}$$

One example of this function is drawn in Figure 4 together with a level of the target service probability. The intersection of the target service probability and the service probability plane gives the maximum cell range that provides the target service probability with the given antenna height.

Now, it is possible to solve the optimum antenna height and the corresponding maximum sector area or cell range which provide a defined target service probability or quality. The result can be presented as a curve of a maximum cell range as function of antenna height (see Figure 5). The maximum cell range in this curve corresponds also to the maximum cell area and thus the optimum performance of the network layout.

3.2. Numerical analysis

First, in the numerical analysis, the dominance area border is solved numerically for the network layouts. Next, the DL SIR analysis is performed both on the worst case point and as an average SIR over the dominance area border. The effect of the path loss exponent on the average SIR values is also analysed. This gives an indication of the sensitivity of the performance of the different network layouts for the base station antenna height.

Also the signal statistics of the different network layouts are analysed numerically over the whole network coverage area. The signal level (pilot power) and $I_{\text{other}}/I_{\text{own}}$ in DL are used to assess the coverage and interference properties of the layouts. The evaluation is performed by utilizing the maximum cell ranges and optimum antenna heights that are the results of the system simulations described in the next section. This enables the analysis of the effect of RF performance to the final system performance.

3.3. System simulations

Mobile radio system performance is affected by random user locations, mobility of users, fading on radio channel and random usage patterns together with range of parameters. System simulations provide the possibility to model the effect of these variables and parameters.

The service probability of the different layouts is analysed with system simulations in WCDMA planning tool [21] which takes into account the random user locations, propagation slope, slow fading, antenna radiation pattern, network configuration, and service types. The tool is setup with a number of network configuration, radio resource management (RRM), service type, network traffic, and propagation model-related parameters.

Only a speech service is used in the simulation as the scope of the study is the assessment and comparison of different layouts for mobile communications. A homogeneous traffic distribution (100 Erl/km^2) is used to load the network. Table 2 presents the sector-level configuration-related parameters, common channel power, and base station RF settings, which are required for the analysis. It also lists the RRM-related parameters for maximum UL and DL loads, power control, and soft handover.

A network of at least 24, 25, and 19 sites is used for the triangular, square, and hexagon-based layouts, respectively, to provide sufficient surrounding environment for the analysis area situated in the centre of the network.

Finally, the service probability is simulated with multiple combinations of cell ranges and antenna heights in order to solve the function (12). The simulation results are interpolated and presented as a plane like the example in Figure 4.

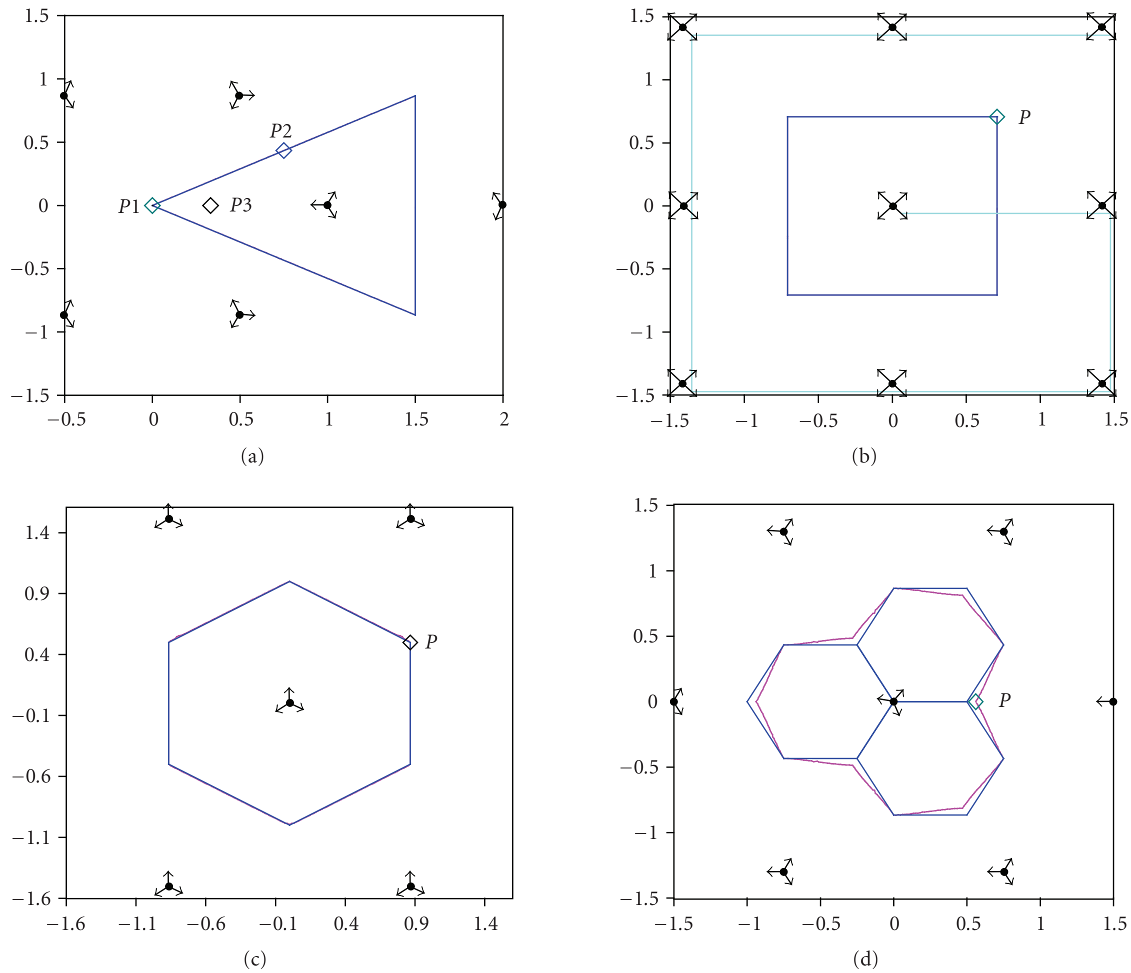

Figure 6: Site dominance area shape for different layouts (slope = 40 dB/dec).

Table 2: System simulation parameters.

Parameter	Value
Orthogonality factor	0.65
Pilot power	33 dBm
P-CCPCH power	28 dBm
S-CCPCH power	33 dBm
P-SCH power	30 dBm
S-SCH power	30 dBm
Noise rise limit-UL	4 dB
Max. node-B TX power	41.5 dBm
Soft handover window	3 dB
Active set size	3
Max. UL power per radio link	21 dBm
Max. DL power per radio link	31 dBm

4. RESULTS

4.1. Numerical analysis results

The site dominance areas of the selected network layouts are plotted first in Figure 6 with propagation slope of 40 dB/dec, which corresponds to a path loss exponent value of 4. This slope value was selected in order to emphasize the possible effect of the slope on the dominance area shape. The results confirmed the theoretical derivation presented in Section 3 as the dominance area of triangular, square, and hexagonal layouts follow exactly the geometrical borders defined by the tessellation. On the other hand, the clover-leaf layout shows in Figure 6(d) some deviation from the geometrical cell shape. This is due to unequal antenna gain of the neighbour cells at the cell border. Further analysis showed that the dominance area shape approaches the geometrical border of the three hexagon clover-leaf shape when the propagation slope decreases.

Next, the results of the analysis of the average SIR over the dominance area borderagainst propagation slope are presented in Figure 7. The results show a clear increase of the SIR when propagation slope increases. The SIR of the triangular and square layouts has clearly higher dependence on the propagation slope. Moreover, the effect of the propagation slope is the highest when the significant portion of the interference is coming beyond the first tier of neighbours. This difference on the effect of the propagation slope leads to a requirement to optimize the

Table 3: Results of SIR analysis on cell dominance area border, slope 35 dB/dec.

SIR at cell dominance border	Triangle	Square	Hexagonal	Clover-leaf
Worst case point (dB)	−7.4	−8.9	−8.2	−4.3
Average (dB)	−3.1	−3.6	−3.2	−3.0

Table 4: System simulation results.

	Triangle	Square	Hexagonal	Clover-leaf
Cell range (m)	977	907	677	800
Antenna height (m)	31.8	40.2	31.4	32.1
Cell area (km^2)	0.414	0.412	0.397	0.415

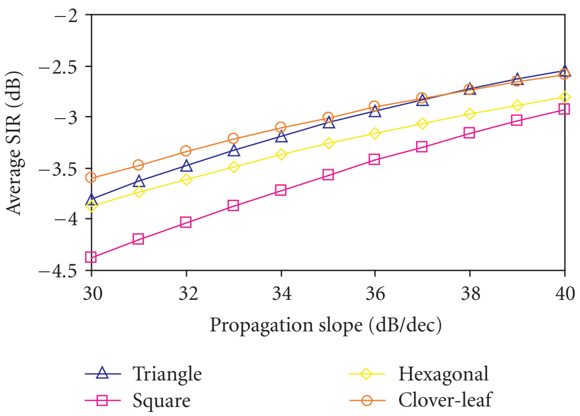

Figure 7: Effect of the antenna height on average SIR at dominance area border for different layouts.

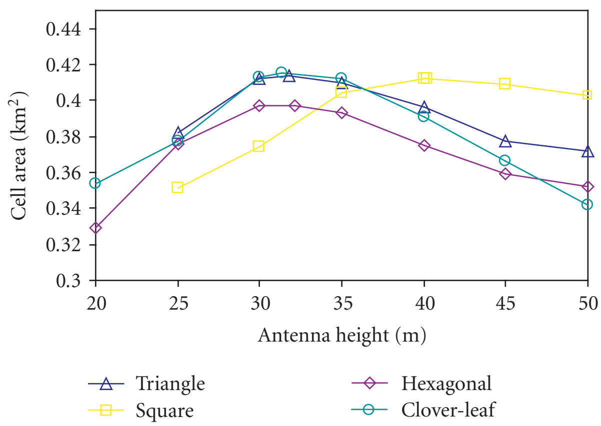

Figure 8: Maximum sector area as a function of antenna height for different layouts.

antenna height when optimum performances of different layouts and configurations are compared.

Table 3 presents SIR at the worst case point and average SIR over the dominance area border for the slope value of 35 dB/dec. The results indicate that the clover-leaf layout provides clearly highest SIR of −4.3 dB at the worst case point and highest average SIR of −3.0 dB at the cell edge. This is due to low number (max. three) of equal signals at any point of dominance area border. The average SIR values for triangle and hexagonal layouts, −3.1 dB and −3.2 dB, respectively, are close to the clover-leaf layout. On the other hand, the square layout provides both the lowest SIR of −8.9 dB at the worst case point and lowest average SIR of −3.6 dB at the cell border. This is mainly due to high level of interference coming from the second tier of neighbours in the network.

4.2. System simulations and signal statistics

The main result of the system level simulation analysis is the maximum sector area, which provides the set target service quality. The maximum sector area can be achieved only at the optimum antenna height. Thus, the results of the effect of the antenna height on the maximum sector area are presented first in Figure 8. The optimum antenna height of the square layout (40.2 m) is clearly higher than with the other layout designs (31.4–32.1 m). This can be partly explained by the higher cell range caused by the dominance area shape. However, the triangular layout has even higher cell range, but does not require higher antennas position. This difference can be explained with the sector shape (small relative area at the high distance) and high level of diversity provided by the six overlapping sectors in this corner area.

Next, the sector area was evaluated with the optimum antenna height of 31.8 m for the triangular, 40.2 m for the square, 31.4 m for the hexagonal, and 32.1 m for the clover-leaf layout. Different layouts provided a maximum sector area of 0.397 km^2 to 0.415 km^2 (see Table 4). This indicates that the system-level performance is quite similar, and no large differences exist in the defined analysis environment. This can be considered quite unexpected because the numerical SIR results indicate a clear difference between the layouts. On the other hand, the 5% decrease of the required base station infrastructure and site investment can be seen significant in estimations of network cost.

In further analysis, the behaviour of the different layouts was studied based on more detailed system-level simulation results. Table 5 presents results of UL I_{other}/I_{own} and SHO overhead. The UL I_{other}/I_{own} levels of 0.88 and 0.89 in triangle

Table 5: System performance at optimum point.

	Triangle	Square	Hexagonal	Clover-leaf
		Sector overlap		
UL $I_{\text{other}}/I_{\text{own}}$	0.88	1.02	1.02	0.89
SHO overhead	27%	26%	25%	27%
		Error causes		
DL E_b/N_o range	13%	11%	14%	13%
DL E_b/N_o (capacity)	2%	19%	6%	1%
UL E_b/N_o range	90%	75%	88%	87%
Noise rise (capacity)	17%	33%	21%	22%

Table 6: Results of the theoretical analysis for signal statistics over network area.

	Triangle	Square	Hexagonal	Clover-leaf
		Pilot level over cell area		
Average (dBm)	−77.5	−77.7	−77.8	−77.1
St.dev (dBm)	4.7	4.6	5.2	4.2
% <−85 (dBm)	4.7%	0.6%	6.0%	0.2%
		DL $I_{\text{other}}/I_{\text{own}}$ over cell area		
Average	0.67	0.71	0.76	0.54
St.dev	0.72	0.58	0.76	0.51
% >2	6.0%	3.0%	6.5%	0.8%

and clover-leaf layouts, respectively, are clearly lower than for the other layouts. This indicates that these layouts can provide higher UL capacity. The SHO overheads of all layouts are at equal level (25%–27%), and do not cause significant difference between the DL capacities of the layouts.

Table 5 presents also the relative share of different error causes, which can be used to understand the network behaviour at the maximum sector area. These results indicate that the layouts are mostly UL coverage limited at this point because 75–90% of the failures involve a limitation of UL power or coverage. The results of square layout show some deviation from the other layouts due to higher proportion of UL (33%) and DL (19%) capacity-related failures.

Next, Figure 9 clarifies further the relative share of coverage and capacity-related failures. Figure 9 presents the relative proportion of the capacity and coverage failures as a function of antenna height. These results were derived from the system simulation results of the clover-leaf layout. Figure 9 shows the trade-off between the coverage and capacity limitation that is present in optimization of any radio network layout. The maximum sector area was achieved at the 32.1 m antenna height and the performance is clearly coverage limited at his optimum point as discussed earlier.

The results of the signal statistics are also summarized in Table 6 in order to complete the performance comparison. The clover-leaf layout provides the highest average signal level of −77.1 dBm with lowest standard deviation of 4.2 dBm around the coverage area, and also the lowest 0.2% share of low signal level area. Also, the coverage of the square layout provides clearly lower probability 0.6% of low signal level when compared to values of 4.7% and 6.0% for

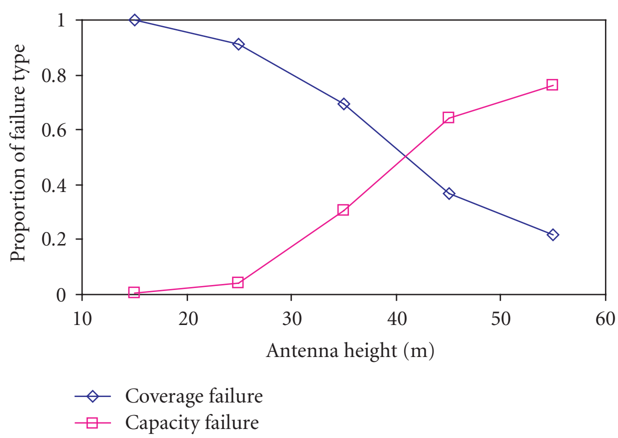

Figure 9: Relative failure type as a function of antenna height. Clover-leaf layout, cell range 800 m, optimum antenna height 32.1 m.

triangle and hexagonal layouts, respectively. Moreover, the sector overlap analysis with DL $I_{\text{other}}/I_{\text{own}}$ follows the same order; clover-leaf layout provides the lowest level of other sector interference DL $I_{\text{other}}/I_{\text{own}}$ with average of 0.54.

After the initial layout analysis, the assessment of the network layouts was extended to different sectorization configurations. The results of these studies indicate that a hexagonal configuration equipped with 6-sector site and narrow 33 degree antennas can provide similar sector area as the other layouts. The main difference is that it requires higher antenna placement than the other layouts; 0.39 km^2 sector area was achieved with 49-metre antenna height.

Table 7: Maximum site areas of 3-4 sector layouts.

	Triangle	Square	Hexagonal	Clover-leaf	Hexagonal
Number of sectors	3	4	3	3	6
Antenna height (m)	31.8	40.2	31.4	32.1	49
Site area (km^2)	1.24	1.65	1.19	1.25	2.38

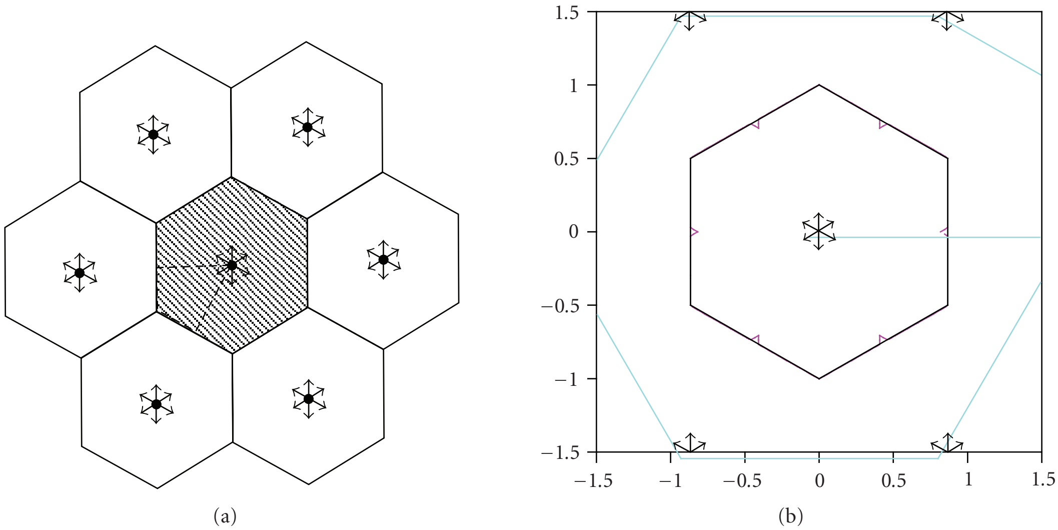

Figure 10: (a) 6-sector hexagon layout and (b) dominance area.

High level of sectorization can be beneficial from network cost point of view as the highest investment and operating costs are typically related to the site location and transmission to the site. Table 7 lists the site areas that can be achieved with the different layouts. The 6-sector layout provides clearly the highest site area.

5. CONCLUSIONS AND DISCUSSION

In this paper, the performances of different tessellations were evaluated for CDMA radio access scheme as a function of base station location, antenna height, and azimuth direction of the antenna.

First of all, it was pointed out that optimum base station height varies significantly for different layout designs in case of CDMA radio access. Next, the results based on numerical SIR calculations showed that clover-leaf layout has a superior performance when compared to the other layouts. And finally, based on more complete system-level simulations, the performance of the triangular and square layouts was shown to be at equal level with the clover-leaf layout. Moreover, the performances of these layouts are clearly better than the performance of traditional 3-sector hexagon layout.

The system simulation results also showed that a 6-sectored configuration was superior in both coverage- and capacity-related scenarios. Especially coverage-related result is interesting due to the fact that a 3-sectored layout is typically preferred in practice in case of pure coverage limited deployment. However, the results showed that the optimum performance can be achieved only when a sufficient base station antenna height can be implemented.

The comparison of numerical calculations and system-level simulations showed that it is not enough to calculate certain "worst locations" for signal-to-interference analysis but a more complete system-level simulation is needed to get reliable results about the behaviour of interference and system performance.

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